DESIGN OF
THE BATHYSCAPH TRIESTE II

BY

HERBERT L. GRAYBEAL

SAN FRANCISCO BAY NAVAL SHIPYARD
MARE ISLAND DIVISION
VALLEJO, CALIFORNIA

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INTRODUCTION

The development of the bathyscaph has provided the oceanographer with a vehicle which will permit him to explore and research even the deepest parts of the oceans. The deep submergence environment presents many unusual considerations for the designer and operator of bathyscaphs. This paper discusses some of these unique problems involved in the development of the Navy's newest bathyscaph, the TRIESTE II.

HISTORY OF BATHYSCAPHS

Figure 1 shows the family of bathyscaphs that has pioneered a new era in oceanographic exploration. All of these craft utilize the basic principle of the bathyscaph which is the same as a free balloon in the atmosphere. The FNRS-2 was built in 1948 by Auguste Piccard with the support of the Belgian National Fund for Scientific Research. He also started the work on its successor, the FNRS-3, with the French in 1953 but soon left to construct the TRIESTE I in Italy. TRIESTE I, as originally designed, was capable of going to 20,000 feet as were its two predecessors. In 1957, the U. S. Navy became interested in deep diving vehicles and purchased the TRIESTE and extended its capabilities to dive to 36,000 feet. This alteration consisted of enlarging the float and installing a new sphere designed for the greater depth. Its historic dive to 35,800 feet in the deepest known spot in the oceans was made in the challenger deep of the Mariannas Trench in 1960. It received additional publicity during the summer of 1963 while searching for the THRESHER which was lost in the Atlantic.

The French are continuing with an improved Bathyscaph names The ARCHIMEDE which is also designed for 36,000 feet. This craft has been down more than 31,000 feet in the Kurile Trench in the Pacific.

In 1962 the U. S. Navy undertook the development of an improved Bathyscaph. This program, sponsored by the U. S. Navy Electronics Laboratory in San Diego and the Bureau of Ships, has resulted in construction of TRIESTE II.

DESIGN CRITERIA FOR TRIESTE II

Throughout the design of TRIESTE II, the basic principles so well proven in TRIESTE I, were to be followed closely. The new float was to be designed to carry either the Terni (20,000 ft.) or the Krupp (36,000 ft.) sphere. Reliability and safety were fundamental requirements. For safety purposes, it was desired to build in sufficient reserve buoyancy to allow for the loss of any two gasoline tanks in case of damage. The surface towing characteristics were to be improved to 10 knots. The electric propulsion system was specified to provide an endurance of 8 hours and a speed of 2 knots using lead-acid type batteries.

DESCRIPTION OF TRIESTE II

The configuration of TRIESTE II is shown in Figure 2. It is a fairly conventional arrangement for a Bathyscaph with ballast tanks fore and aft and gasoline tanks through the midsection. The hull is tear-drop shaped in plan view to provide buoyancy forward, to reduce resistance, and improve surface performance. The design provides ample deck space which facilitates surface operations in preparing for dives. After the ballast tanks are flooded, the weight of the Bathyscaph is controlled by releasing iron shot from the forward and aft shot tubs through magnetic valves. Buoyancy is controlled by venting gasoline from the maneuvering tank. The maneuvering tank is always open to sea pressure to insure that internal and external pressure are equalized. The sphere is located well forward and is recessed in the hull to reduce draft and hydrodynamic drag. The eyes and ears of this craft include a scanning sonar, lights, and cameras in the bow, and underwater telephone, television, and fathometers located on the bottom aft of the sphere. A scientific well extends vertically through the forward ballast tank to provide free flow of water to scientific instruments. The propulsion plant consists of twin propellers and motors mounted aft. Batteries are stowed in battery tanks in the aft ballast tank and under the superstructure. A mechanical arm and basket are located admidships on the bottom for retrieval purposes. The shot tubs and retrieval equipment are supported by release magnets so that they may be jettisoned in an emergency. Since the pressure inside all of the tanks is equalized with external pressure, there is no requirement for heavy structural construction. The only part of the craft that must resist external pressure is the sphere itself. Batteries and motors are contained in oil which is also equalized with sea pressure.

DESIGN OF THE TRIESTE II

This type of vehicle must be designed to meet two basic operating conditions - surfaced and submerged. The design of the float for surface conditions was influenced by the distribution of weight and the need to provide improved towing characteristics with a simple and economical hull form. The performance of this hull was checked out by towing a model in the University of California and David Taylor Model Basin tanks. Since the surface design techniques are not unique, there is little purpose in discussing them in detail in this paper.

Unique Engineering Problems

For the submerged condition, the equilibrium of a Bathyscaph is governed by the well-known principle of Archimedes relating weight and displacement. Many conventional submerine design techniques are applicable to a Bathyscaph but there are a number of unique engineering considerations. The basic difference between a submarine and a Bathyscaph is that most of the submarine's buoyant volume is made up of air surrounded by a pressure hull while the buoyant volume of a bathyscaph is principally a light-weight liquid, such as gasoline surrounded by light structure. While a submarine's volume is affected to a degree by pressure, the bathyscaph's buoyant volume is affected more significantly. This requires vigilance on the part of the designer to anticipate all effects of pressure.

Compression Effects

Figure 3 shows the compressibility of both sea water and gasoline. It will be noted that, at 36,000 feet submergence, the gasoline volume is reduced by about 10 per cent. At the same depth, salt water is compressed 5 per cent and the densities are affected proportionately. This phenomenon has a significant effect on the amount of variable ballast that must be carried. For instance, on TRIESTE II, 24,600 pounds of iron shot must be dropped during a dive to 36,000 feet to maintain neutral buoyancy. The volume of gasoline that is lost due to compression is replaced by salt water.

Temperature Effects

Another variable which is a direct function of pressure is the change in temperature due to adiabatic compression or expansion. As the bathyscaph descends, the gasoline is compressed and it increases in temperature. This effect is gradually offset by the loss of heat from the hull as the ambient temperature of the ocean decreases with

depth. If the bathyscaph remains at depth for an extended period, the gasoline temperature approaches the ocean ambient which is near freezing. While surfacing, the drop in temperature due to adiabatic expansion can cause problems of freezing in any pipe which contains salt water. All pipes used to interconnect the gasoline tanks are sized to allow for this condition. If one of the compensating pipe lines was to freeze, the gasoline tanks would rupture due to differential pressure.

Stability Problems

In any submerged body, the center of buoyancy must remain above the center of gravity if the body is to remain upright. In a bathyscaph several variables affect both buoyancy and weight as depth increases. The compression of the gasoline permits sea water to enter at the bottom of the compensating tank thus adding low weight which must be compensated by dropping shot. The combined effect of adding low weight and dropping high weight causes the center of gravity to shift downward initially and stability increases. In the event of an emergency, the shot tubs and retrieval gear can be dropped with a significant loss of weight which is relatively low and stability can become marginal. The bathyscaph is designed to be able to recover from the loss of any two gasoline tanks, so a reserve of 15,600 pounds of shot is carried for this purpose when diving to 20,000 feet.

Payload Determinations

TRIESTE II is capable of carrying significant payloads of scientific equipment. But these loads cannot be positioned indiscriminately. Three conditions must always be met. The bathyscaph must maintain equilibrium, stability, and a normal attitude. Equilibrium is the condition for which weight and buoyancy are equal. Stability refers to the ability to stay upright. Attitude refers to the pitch and roll angles. In accounting for these requirements, the following interdependent parameters must be considered: Deck load and its longitudinal location, initial shot in each tub and its vertical center of gravity, fixed ballast in the skeg, fixed ballast in the forward ballast tank, and the scientific equipment and its location. The operators must consider all of these parameters in planning a dive to a specified depth.

To assist the operators, a series of studies of various load and ballasting conditions have been charted. The first consideration is dictated by the depth of dive. Figure 4 indicates the requirements for the amount of shot that must be carried as variable ballast for the range of depths. This quantity includes the amount required to

compensate for the compression of the gasoline, plus an allowance for a specified retrievable load plus a quantity for maneuvering and a reserve to account for the flooding of any two gasoline tanks. Once the variable ballast has been determined, the remainder of the buoyant capacity of the float is available for payload or fixed ballast.

The distribution of the load and fixed ballast is the second consideration. Figure 5 illustrates the problem of fore and aft distribution of the load and ballast for one condition with full shot tubs and a specified minimum stability. After the weight and longitudinal center of gravity of the payload are determined, then the amounts of fixed ballast to be located in the skeg and forward ballast tank are easily found. In extreme cases, if the load is far forward or aft, it is necessary to remove shot from one of the tubs to maintain a reasonable trim.

The third consideration is the vertical location of the load or ballast and its effect on stability. After the vertical center of gravity has been located, figure 6 is used to determine the stability under various conditions. The top line shows the stability for the shallow submerged condition. During a normal dive the stability improves with depth. The middle line shows the loss of stability if two gas tanks are holed. If both shot tubs are dropped in an emergency, the stability drops to the lower line. The recommended minimum stability for starting a dive is indicated by the vertical dotted line.

The foregoing discussion illustrates a number of the various parameters and phenomena which must be considered by the naval architect when designing a deep-diving bathyscaph. The operators of this type of craft must also have a clear understanding of these requirements and conditions if operations are to be conducted safely. The basic design philosophy, which is heartily endorsed by the operators, is that the number of surfacings must be exactly equal to the number of dives.

Propulsion System

TRIESTE II is provided with three electric propulsion motors delivering 5 shaft horsepower each to the propellers through individual reduction gears at 110 R.P.M. The propulsion units are located at the stern, one on the centerline and one to port and starboard. They provide thrust forces in essentially the deck plane only. The motors are rated nominally at 120 V.D.C. and are shunt wound. No shunt field control is provided. Regulations of thrust applied for ahead and astern motion, as well as maneuvering is accomplished by turning selected motors on and off and by reversal. Conventional starting and reversal equipment is used. Armature current is limited to 200% in the extreme case, which occurs in a plug reversal. The propulsion units and starting equipment are pressure compensated. The motors and gears are filled with a low-viscosity silicone fluid and the controllers with industrial transformer oil.

The BATHYSCAPH designer, for state-of-the-art reasons, is presently limited to a battery as the source of energy. The two principal batteries employed are the conventional lead-acid or the silver-zinc. A choice is made between the two by balancing naval architectural advantages associated with the silver-zinc (smaller, lighter) against the considerable economic advantages of the lead-acid. Progressing from the D.C. source of power, and again for state-of-the-art reasons, the designer presently chooses a D.C. motor - not because the D.C. motor offers significant advantages over an A.C. motor but because proved power conversion devices appropriate to the conditions are not yet available. Much work is being done in this field and we are on the threshold of being able to install A.C. propulsion systems. This step will permit a wide range of speed control of individual motors, will enable the use of wet motors, will eliminate commutator problems, and probably, conserve weight. In the present BATHYSCAPH design, it would enable us to go to twin-screw propulsion rather than triple screw.

OPERATING EXPERIENCE WITH TRIESTE II

Figure 7 is a picture of TRIESTE II as it appeared when launched in January 1964. TRIESTE II was designed and built at Mare Island Division, San Francisco Bay Naval Shipyard, Vallejo, California. It was delivered to the U. S. Navy Electronics Laboratory in San Diego in November 1963 for outfitting and was launched in January 1964. Its first dive was conducted in February and this was followed by a series of about 15 dives to test its operating characteristics. Maximum depth achieved in this period was about 4200 feet. In April 1964, it was shipped to Boston Naval Shipyard to be equipped to continue exploratory and research work in the area of the THRESHER sinking in the North Atlantic. This assignment was successfully concluded with the location and photographing of the major portions of the hull of the THRESHER. TRIESTE II has since been returned to San Diego and is now assigned to Submarine Squadron Three. Currently, it is being outfitted for further projects associated with the Navy's Deep Submergence System Project.

PARAMETRIC STUDIES FOR BATHYSCAPH III

Following the experience with TRIESTE II, studies were undertaken to develop the design criteria for the next generation of bathyscaph which is now being developed at Mare Island. A series of parametric studies were developed to cover such factors as buoyancy - material, hull materials, sphere materials, depth, and payload considerations. To date all bathyscaphs have used gasoline as the buoyant medium. Gasoline is hazardous, expensive, and is more compressible than sea water. There is an urgent need to develop a better buoyancy material. The present development work is leading toward a syntactic plastic material which is made up of tiny micro-balloons encased in plastic.

It has about the same density as gasoline but is less compressible. It is a solid material that is formed by a thermosetting process. The use of a solid buoyancy material has a significant impact on the structural configuration of a bathyscaph. The buoyancy material can easily be removed from a gasoline bathyscaph but syntactics are more permanent. Consequently, the structure must be heavier to permit the lifting and transporting of the bathyscaph, or the syntactic must be removable. The dry weight of a bathyscaph is definitely limited by crane capacity in many areas. However, syntactics offer many advantages. It is expected that this new buoyancy material will be available for practical application in about 1 year.

Figure 8 illustrates the effect of various materials on the size of a bathyscaph. Thus far, the hulls and spheres have been made of steel. The use of aluminum hulls and aluminum or titanium spheres will permit significant reductions in overall size. Figure 8 also shows the effect of depth on the size of a bathyscaph. It may be noted that it requires a 25% larger bathyscaph to dive at 36,000 feet than is required for 20,000 feet.

Figure 9 indicates the areas of the oceans that lie at various depths. Note that about 98% of the ocean is less than 20,000 feet deep. It is obvious that a bathyscaph designed to go to the deepest part of the ocean will increase the available ocean area by only 2% over that which can be covered by a 20,000 foot bathyscaph. For this reason, and since the novelty of the deepest dive no longer exists, the next generation of bathyscaph will probably be designed for only 20,000 feet.

HULL DESIGN

The hull configuration of TRIESTE II was influenced by the need for better seaworthiness under tow, economical construction, larger battery, reduced draft, and an improved sphere location. It was designed as an oceanographic research vehicle with the capability to dive to any depth with limited maneuverability and endurance. The design characteristics were determined before the THRESHER accident, so it was not ideally suited for that mission. However, it proved to have many advantages over the original TRIESTE.

The oceanographers' experience with bathyscaphs has developed the need for more endurance and maneuverability. The next bathyscaph will therefore have a more refined hull form with additional propulsion controls. Figure 10 shows a comparison of the TRIESTE II type of hull compared to the more streamlined type. Towability and protected deck

space for diving preparation dictates the need for the faired superstructure. Model tests will be used to check surface characteristics, submerged resistance, and maneuverability.

Vertical dynamic stability is also an important design consideration for a bathyscaph. Since the transit time from the surface to the bottom and back again can consume a large portion of the available diving time, it is desirable to move vertically as fast as safety will permit. It was found in TRIESTE II that a rapid ascent resulted in uncomfortable oscillations and gyrations. Special consideration will be given to this feature in future designs.

SPHERE DESIGN

The existing spheres have been made of alloy steel with a yield of about 120,000 psi. Figure 11 illustrates the latest design which is currently being manufactured. It is made of two hemispheres machined from one piece forgings. This 7' sphere has been selected as a standard size that will be equipped to carry three men. The engineering problems associated with the internal arrangement of spheres involve many fields of human engineering and life support systems. This program is destined to receive much more engineering attention in the future.

Since the sphere is the only part of a bathyscaph which must resist pressure, its design is governed by the design depth and the materials. There is much work being done today in the field of developing new materials to withstand the tremendous pressures of the ocean. Figure 12 illustrates the limitations of the various materials that are being considered for submarine hulls. This chart shows the buoyancy limitations of the materials. For bathyscaph spheres it is not essential that they have positive buoyancy, but lighter spheres made of stronger materials would have a significant effect on reducing the overall size and cost of the bathyscaph. The next major step forward in this field will be the application of titanium. Industry now contends that they are able to deliver a 90" titanium sphere that will carry a crew of three to 20,000 feet with reserve buoyancy of about 4,000 lbs. But the consideration and testing of such a sphere remains to be done.

THE FUTURE OF BATHYSCAPHS

The bathyscaph has proven to be an effective vehicle which has permitted man to make the first explorations of inner space. But time will probably show that it is only an interim vehicle until new materials and techniques permit us to build submarines to go to the

depths of the oceans. The bathyscaph is comparable to the free balloon or the dirigible in the development of aviation. The state-of-the-art in submarine design today is providing craft that have the potential design capability to go down more than 10,000 feet. But none of these experimental craft have achieved depths beyond a few thousand feet; so the bathyscaph will continue, for some time to come, to be the only type of vehicle with the capability to explore all the depths of the oceans.

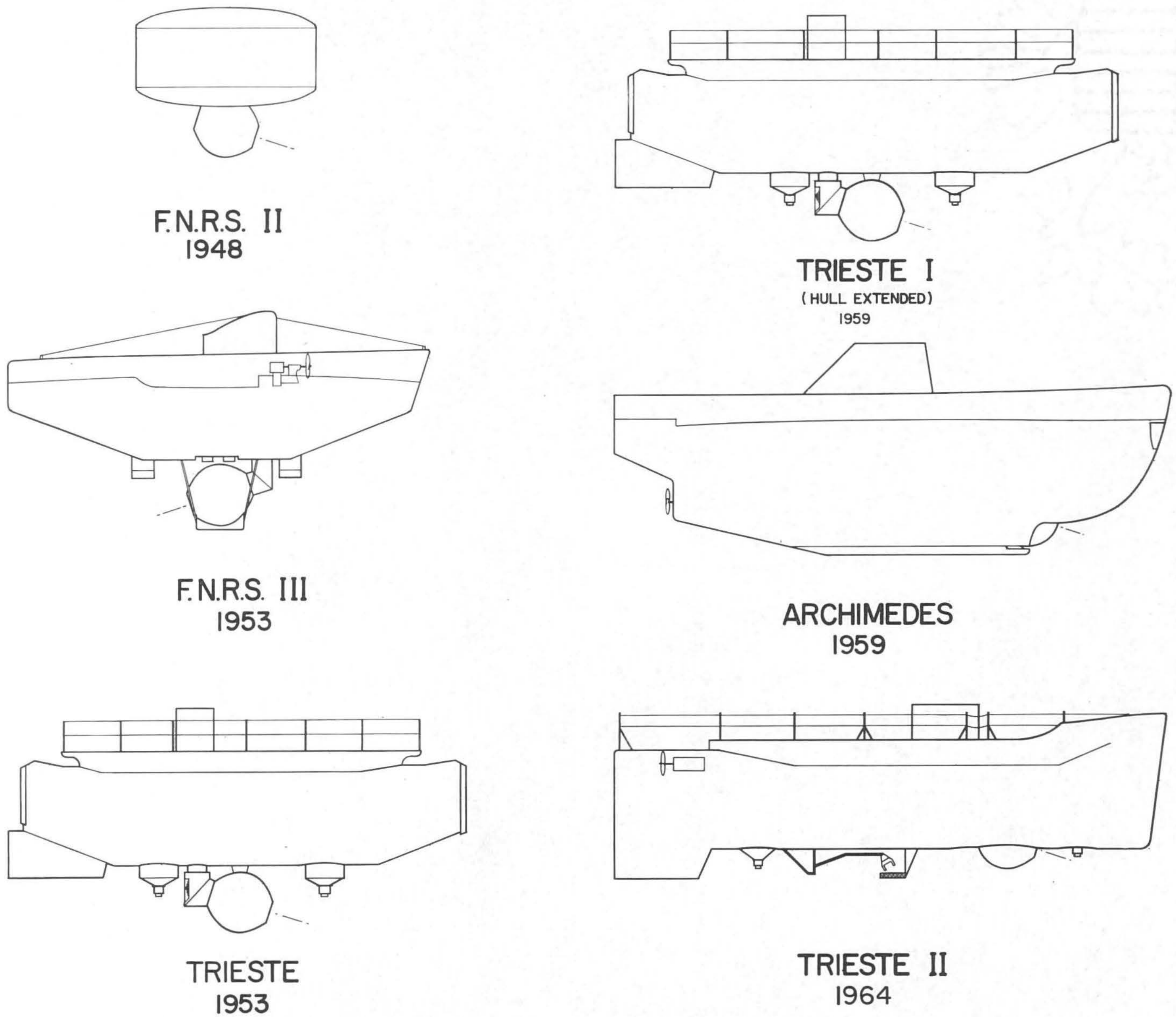

F.N.R.S. II
1948
TRIESTE I
(HULL EXTENDED)
1959
F.N.R.S. III
1953
ARCHIMEDES
1959
TRIESTE
1953
TRIESTE II
1964

Fig. I

TRIESTE I
F.N.R.S. II
1948
ARCHIMEDES
1959
F.N.R.S. III
1953
TRIESTE II
1964
TRIESTE
1953

Fig. 1

BATHYSCAPH TRIESTE II

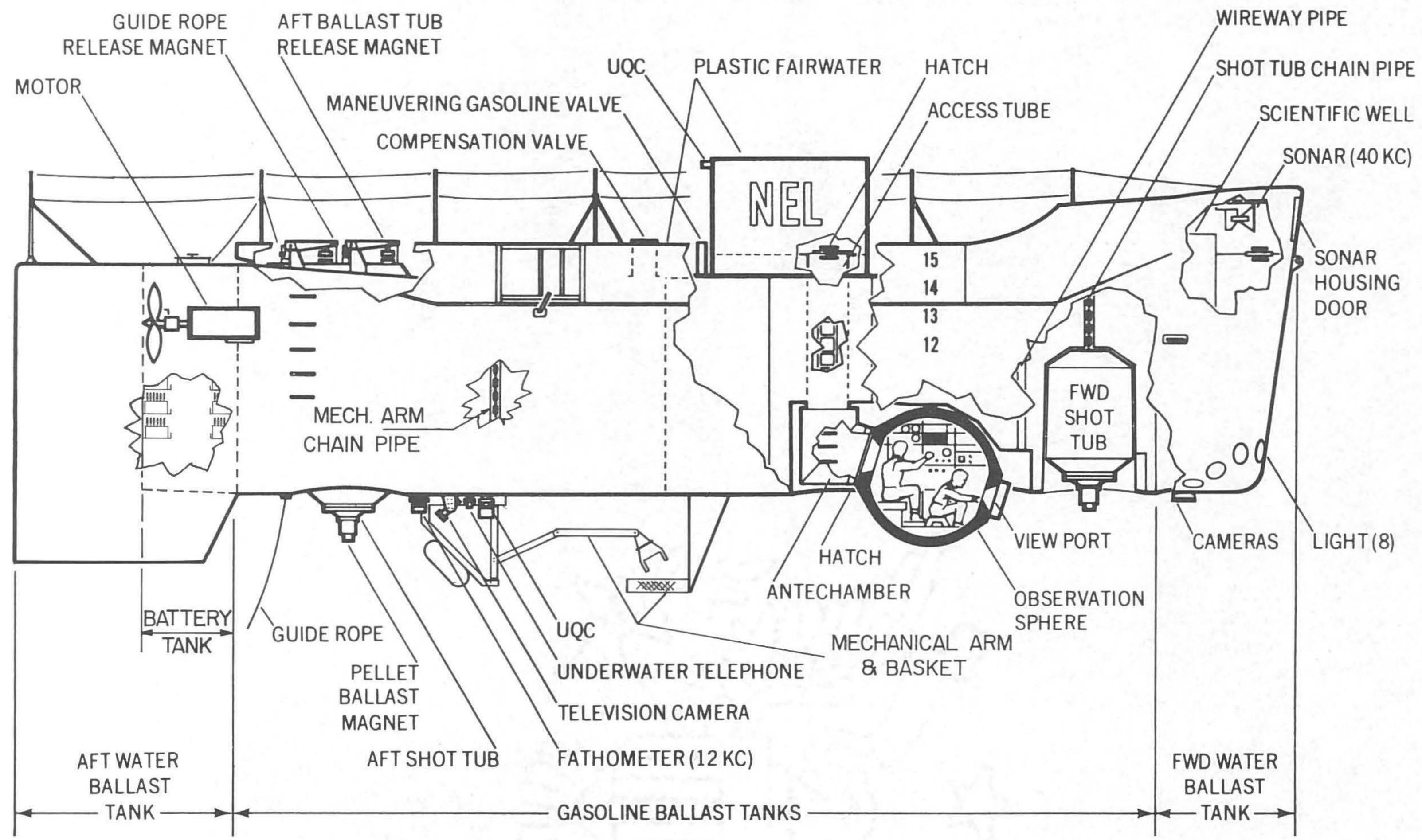
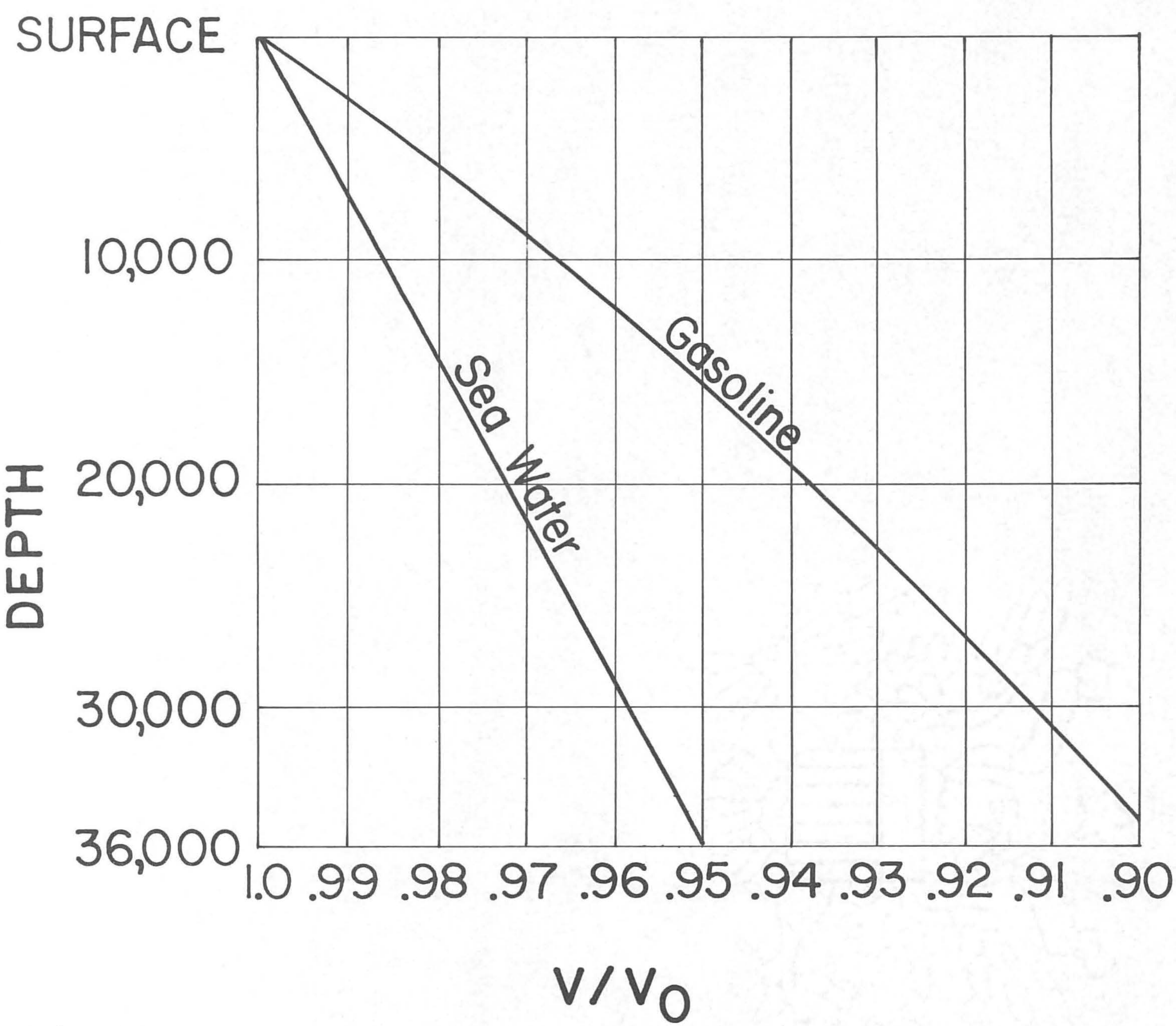
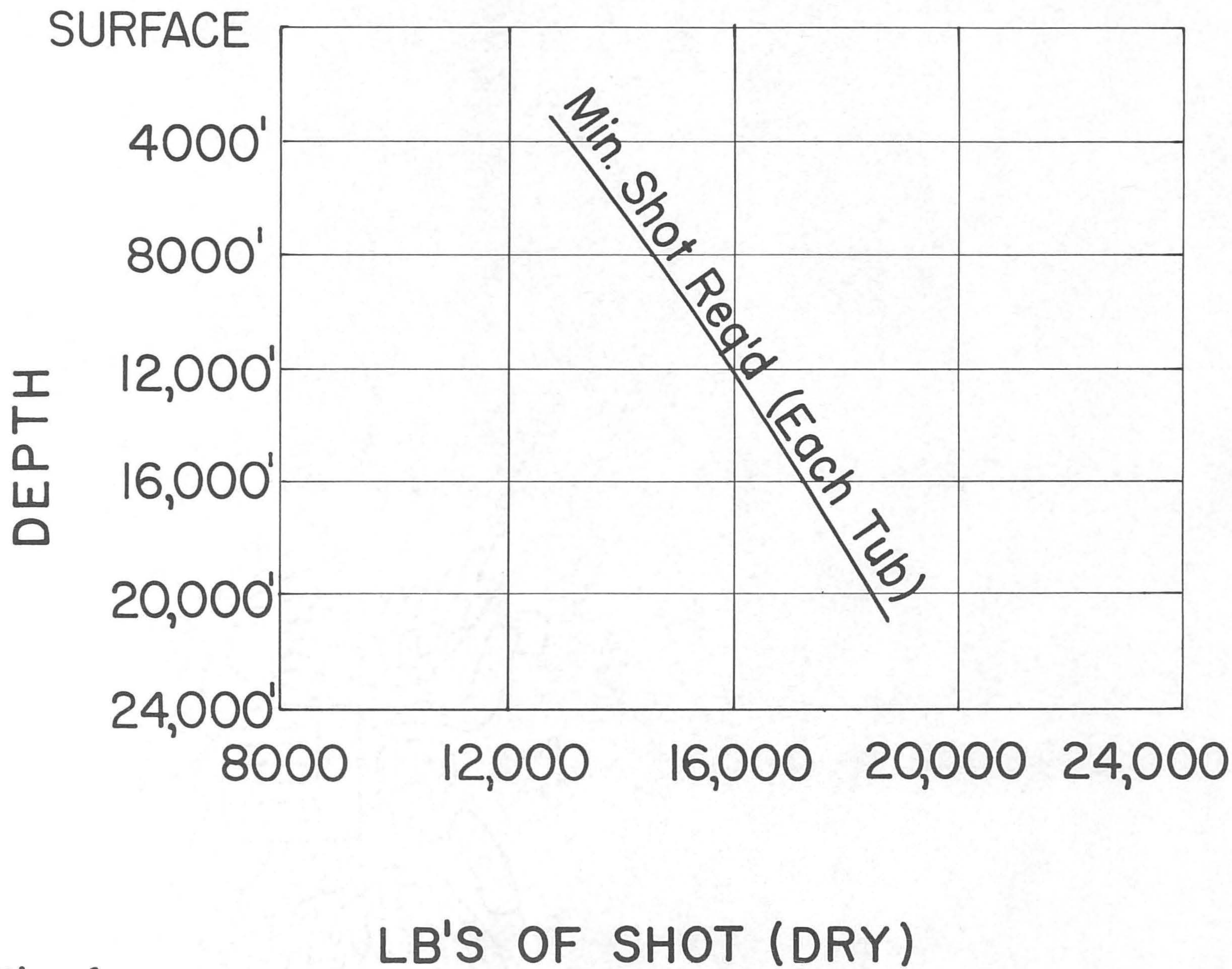


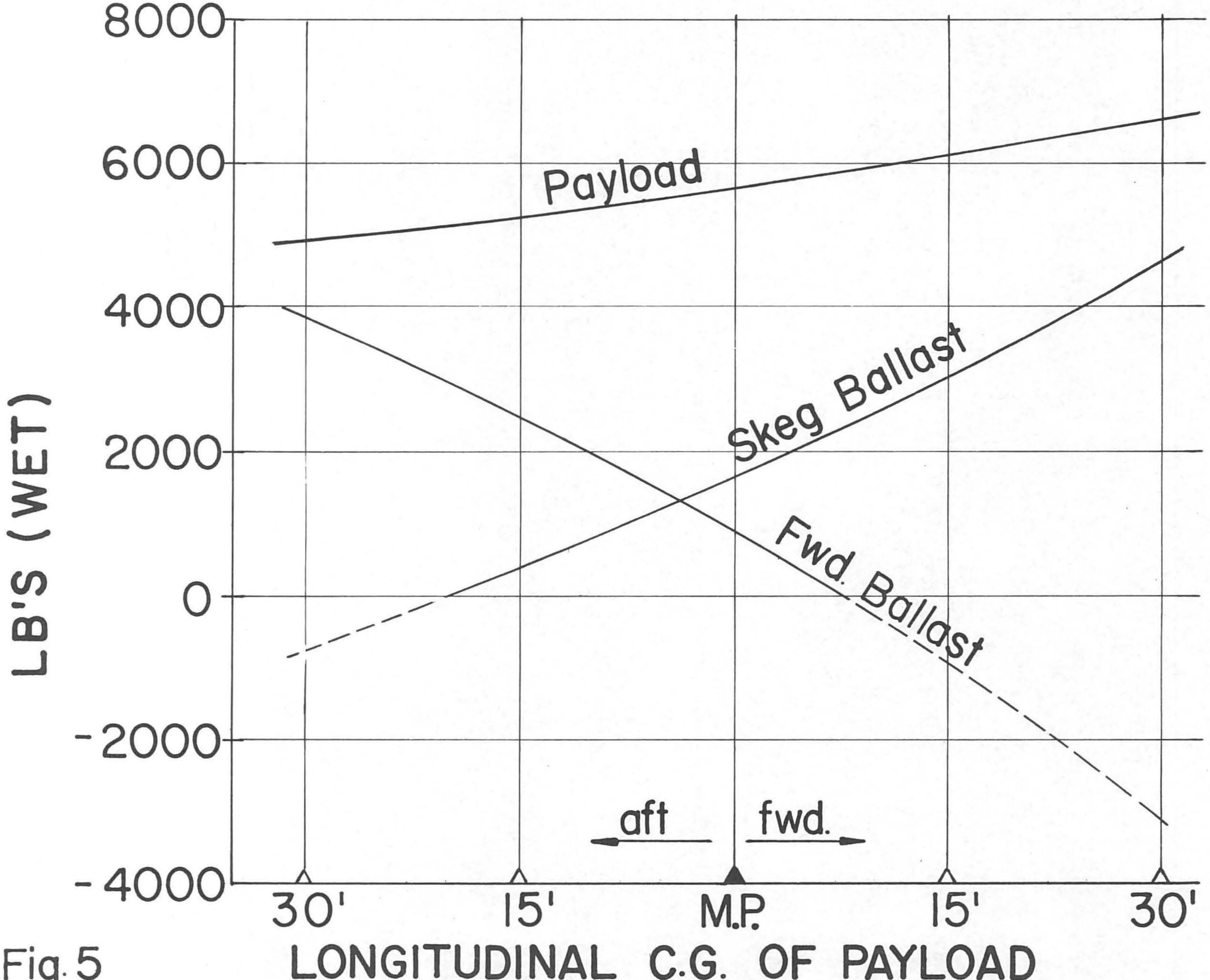
Fig. 2


SURFACE
10,000
20,000
30,000
36,000
DEPTH
Gasoline
Sea Water
1.0 .99 .98 .97 .96 .95 .94 .93 .92 .91 .90
V/VO
Fig. 3



SURFACE
4000'
8000'
12,000'
16,000'
20,000'
24,000'
DEPTH
Min. Shot Req'd (Each Tub)
8000
12,000
16,000
20,000
24,000
LB'S OF SHOT (DRY)

Fig. 4



8000
6000
4000
2000
0
-2000
-4000
LB'S (WET)
Payload
Skeg Ballast
Fwd. Ballast
aft
fwd.
30'
15'
M.P.
15'
30'
LONGITUDINAL C.G. OF PAYLOAD

Fig. 5

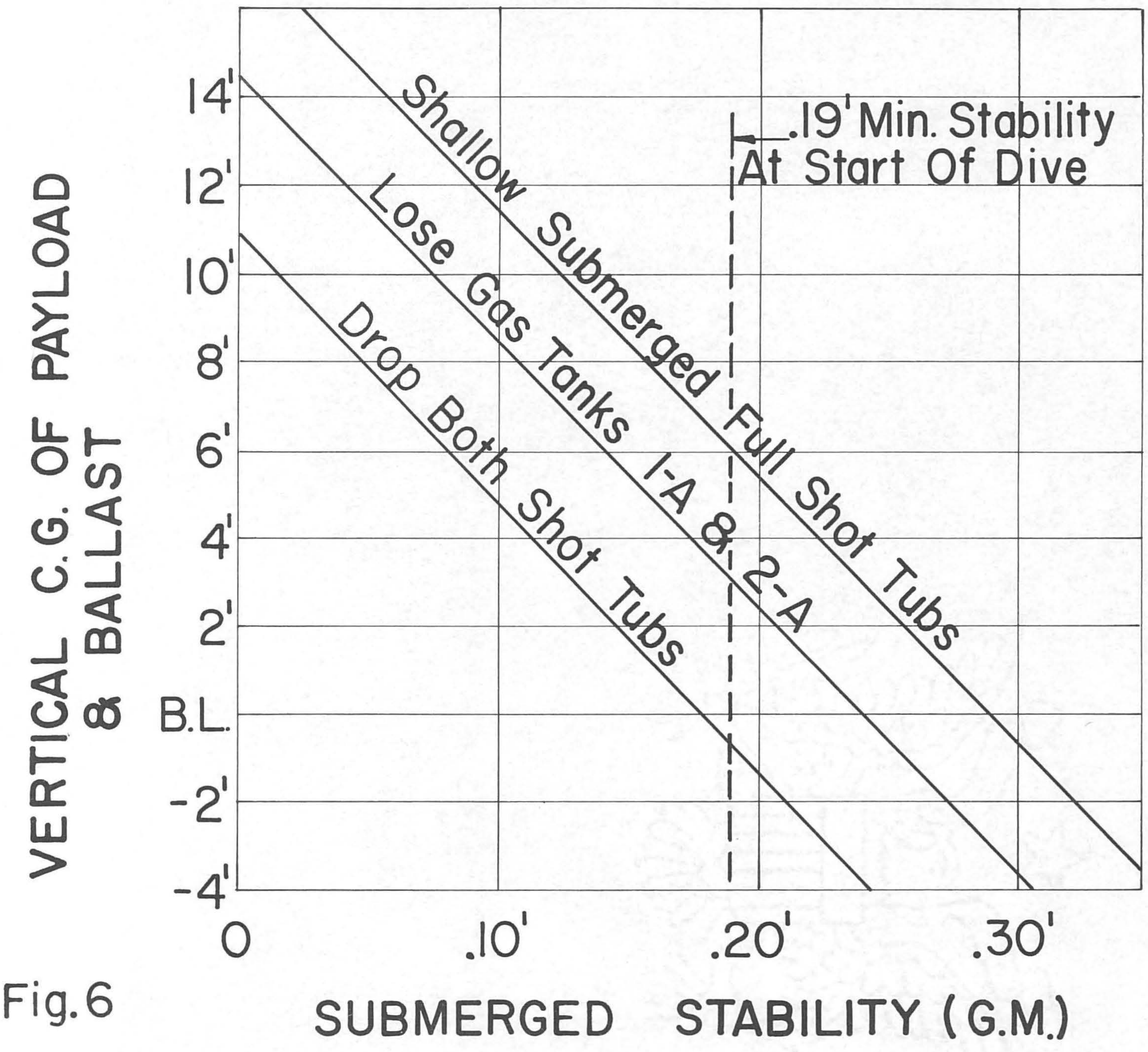
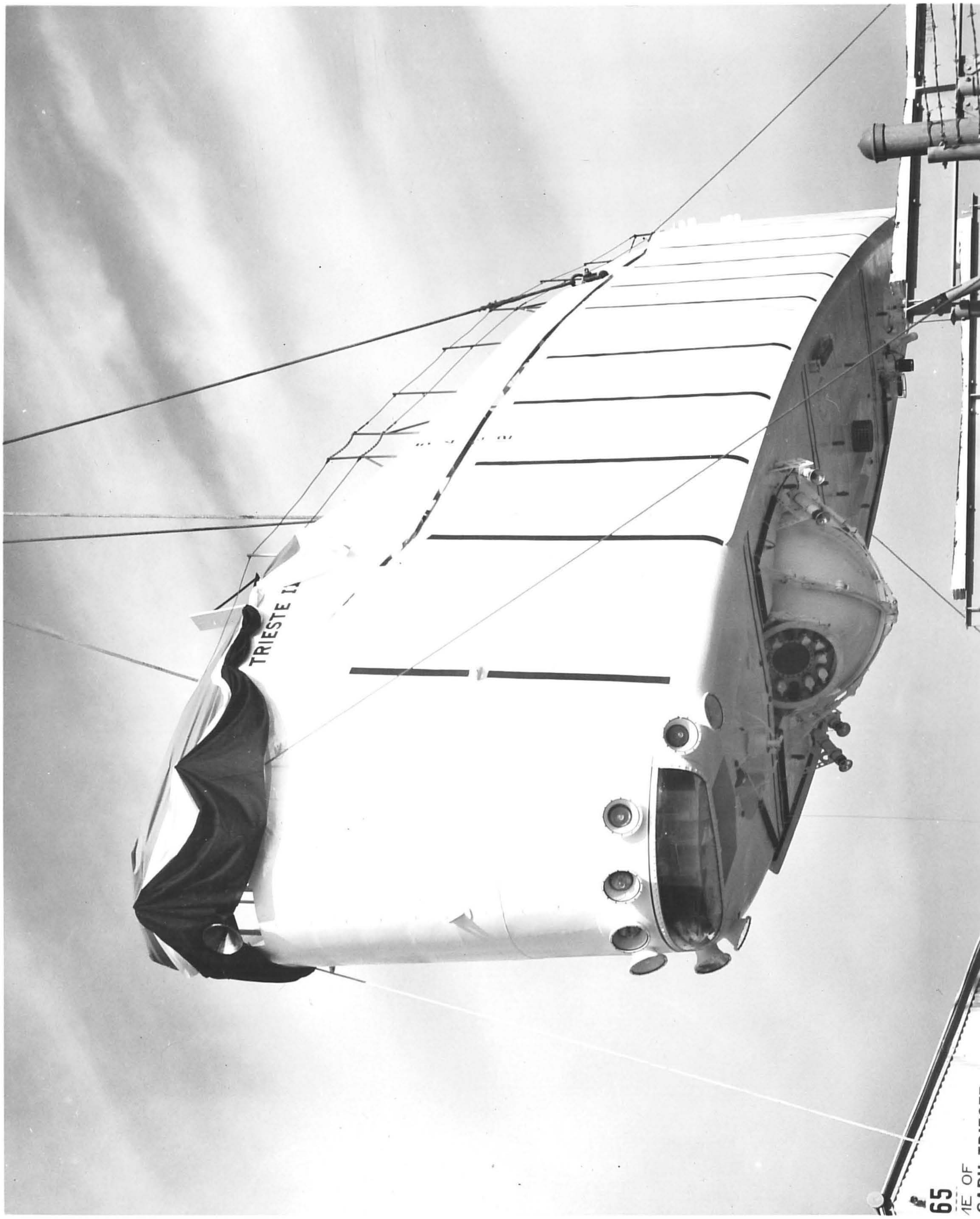
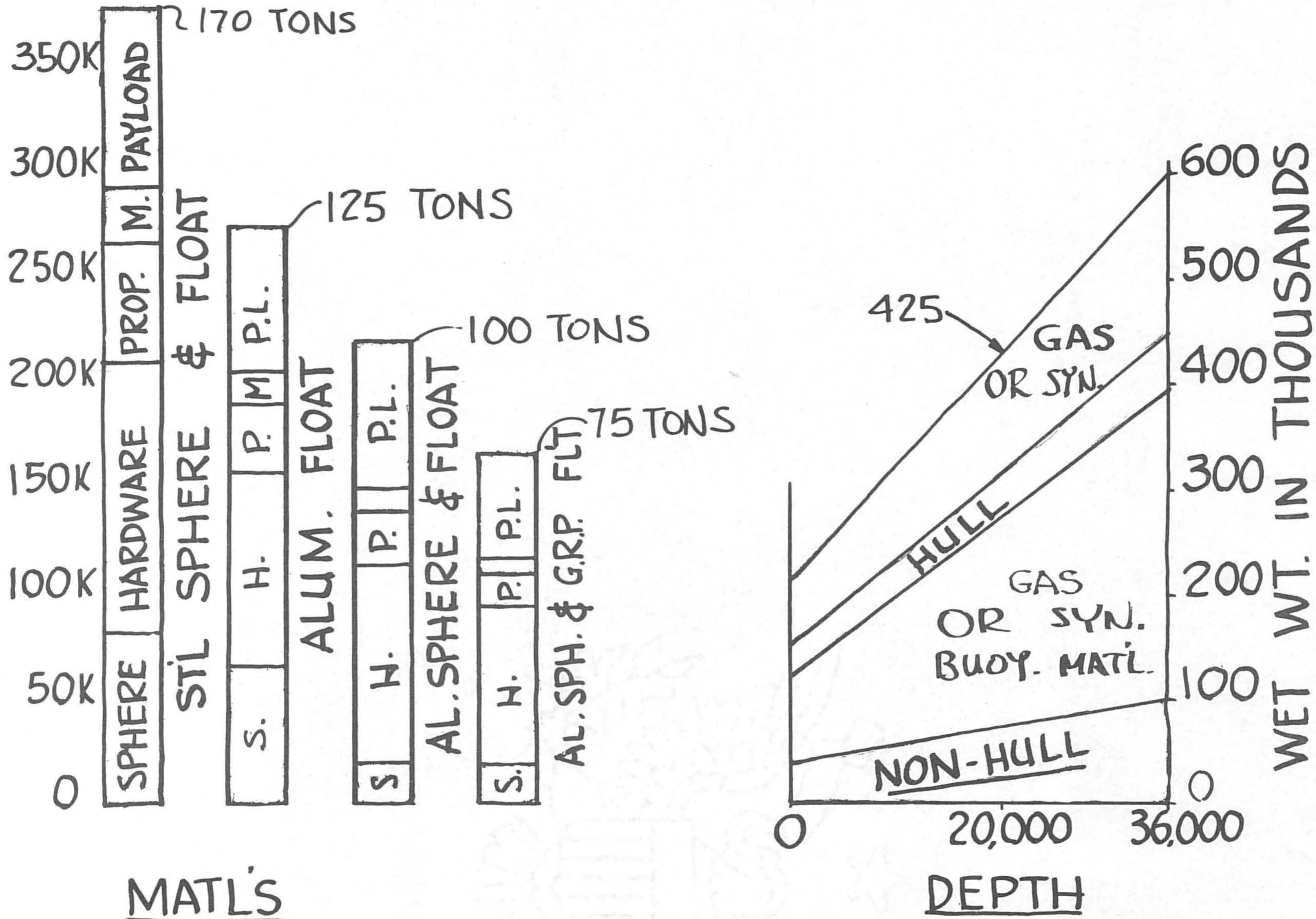

VERTICAL C.G. OF PAYLOAD & BALLAST
14'
12'
10'
8'
6'
4'
2'
B.L.
-2'
-4'
0
.10'
.20'
.30'
Shallow Submerged Full Shot Tubs
Lose Gas Tanks 1-A & 2-A
Drop Both Shot Tubs
.19' Min. Stability At Start Of Dive
SUBMERGED STABILITY (G.M.)

Fig. 6

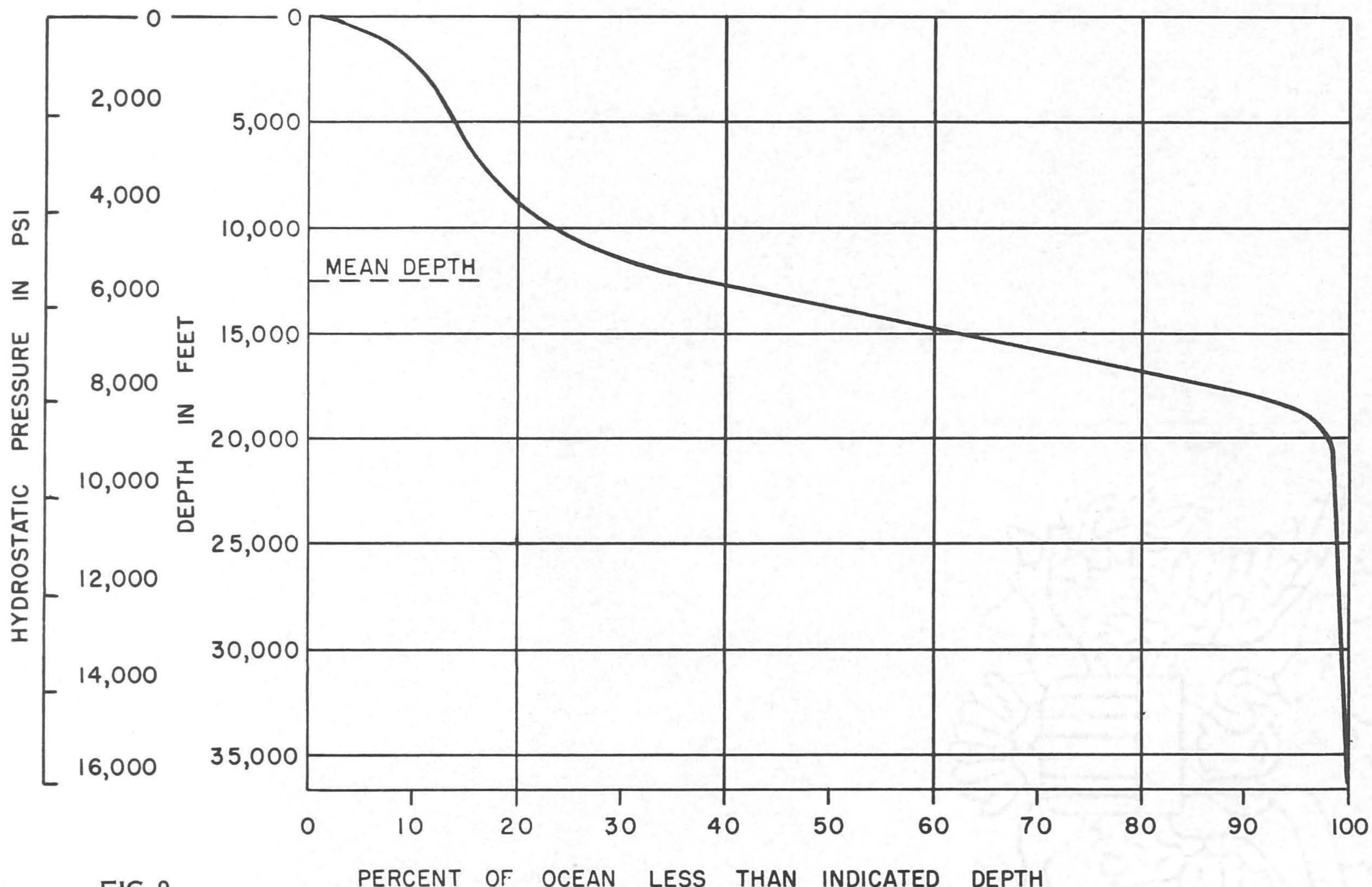

TRIESTE II



BATHYSCAPH SIZE PARAMETERS

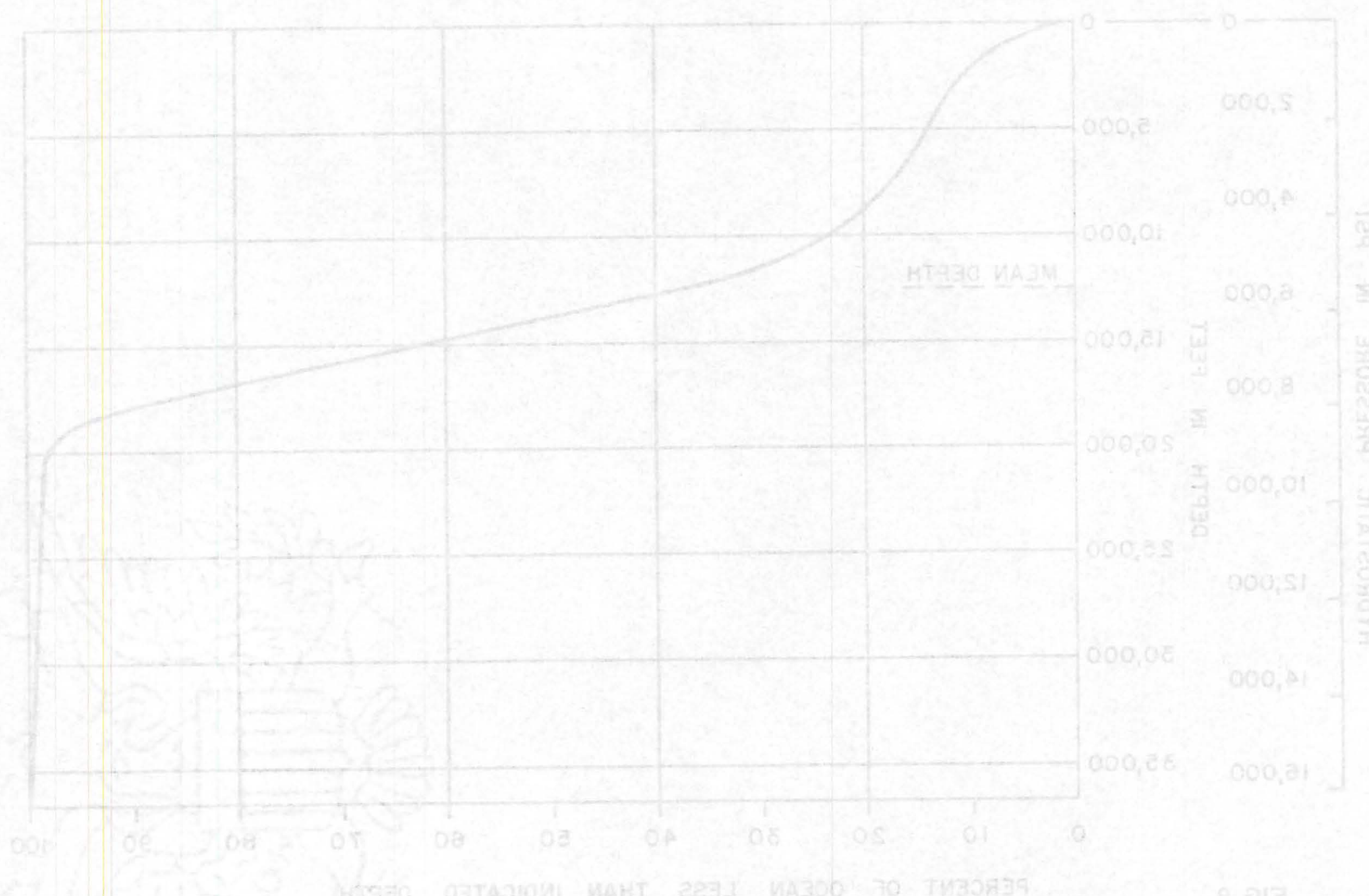
FIG 8

BATHYSCAPH SIZE PARAMETERS
MAT'LS
DEPTH
WET WT IN THOUSANDS
0
100
200
300
400
500
600
36,000
20,000
0
NON-HULL
BUOY. MAT'L
OR SYN.
GAS
HULL
OR SYN
GAS
425
0
50K
100K
150K
200K
250K
300K
350K
SPHERE
HARDWARE
PROP.
M.
PAYLOAD
STL SPHERE & FLOAT
170 TONS
S.
H.
P
M
PL.
ALUM. FLOAT
125 TONS
S
H.
P
PL.
AL. SPHERE & FLOAT
100 TONS
S
H.
P
PL.
AL. SPH. & GRP. FLT.
75 TONS
FIG. 8



HYDROSTATIC PRESSURE IN PSI
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
16,000
DEPTH IN FEET
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
MEAN DEPTH
0
10
20
30
40
50
60
70
80
90
100
PERCENT OF OCEAN LESS THAN INDICATED DEPTH

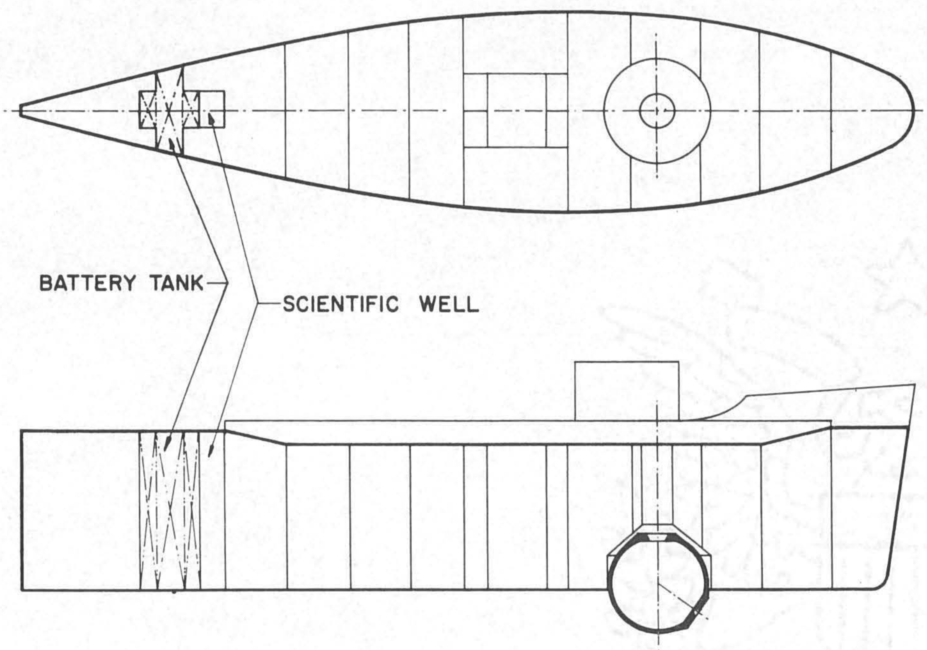
FIG 9



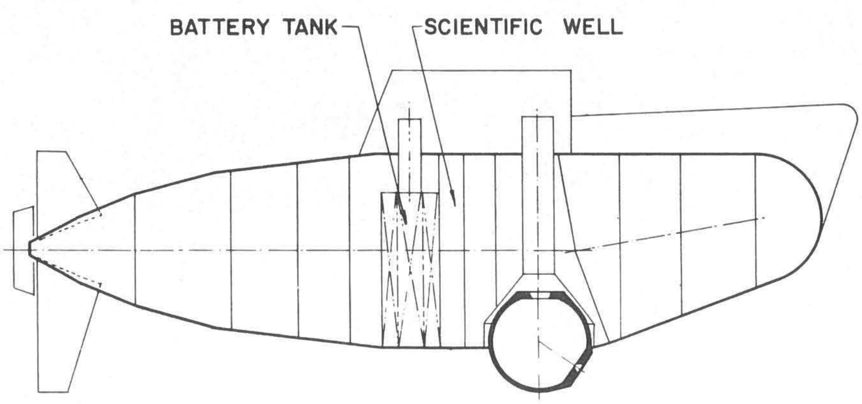
HYDROSTATIC PRESSURE IN PSI
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
16,000
DEPTH IN FEET
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
MEAN DEPTH
PERCENT OF OCEAN LESS THAN INDICATED DEPTH
0
10
20
30
40
50
60
70
80
90
100

FIG 9

SCHEMES

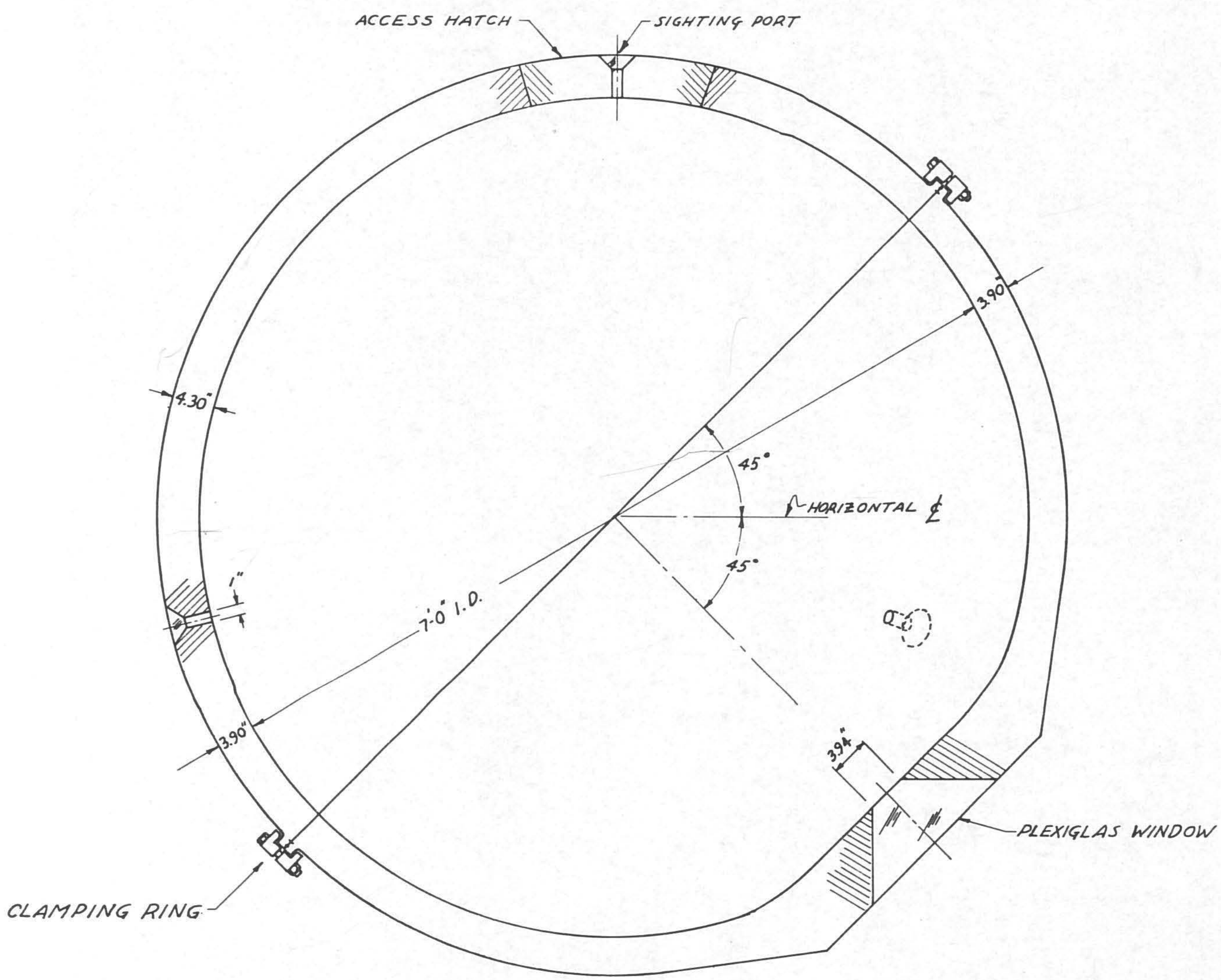


TRIESTE TYPE



BODY OF REVOLUTION

FIG 10



SECTION AT ℄ OF SPHERE

FIG 11

SECTION AT ℄ OF SPHERE

FIG 11

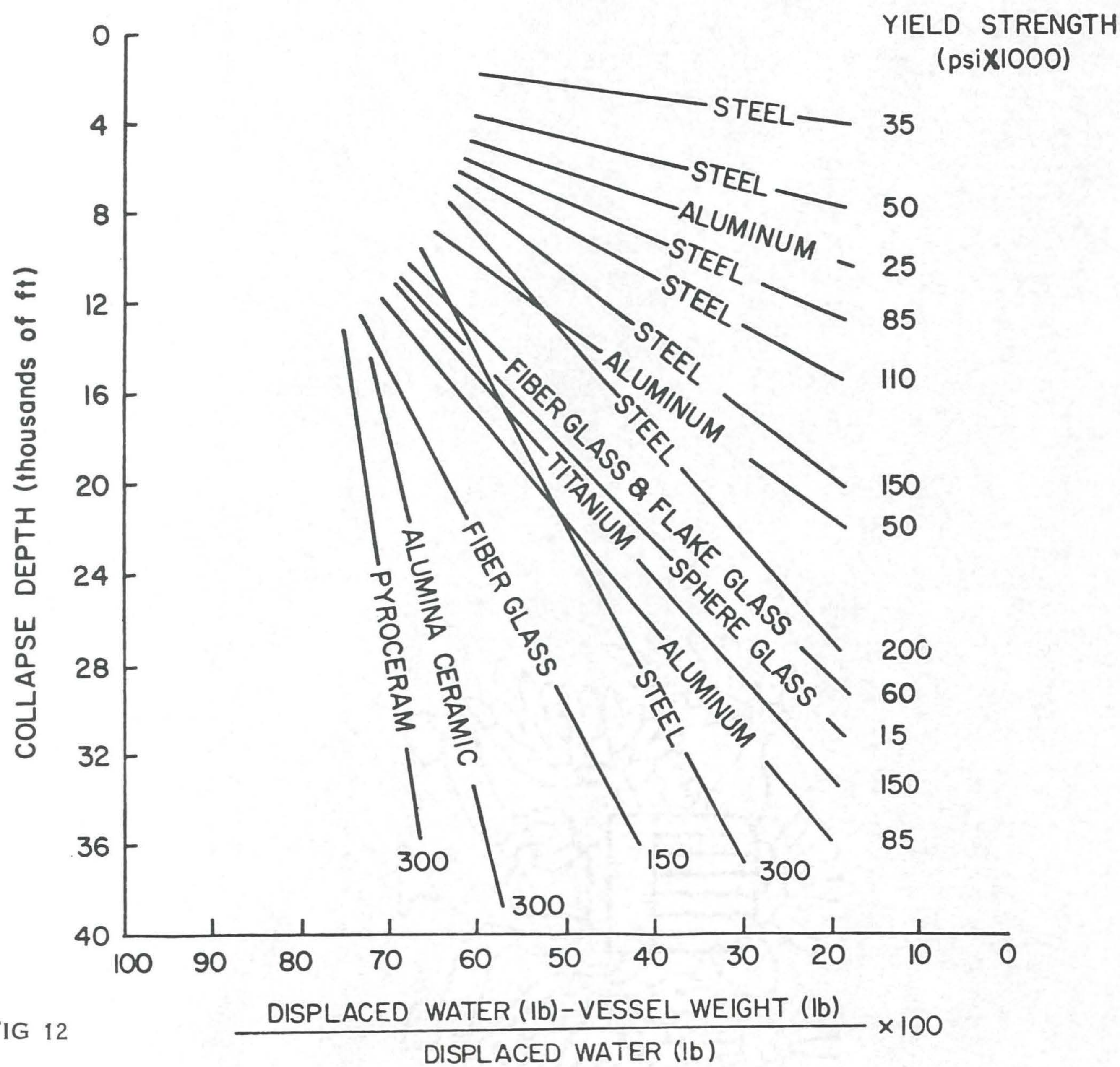

YIELD STRENGTH (psi X 1000)
COLLAPSE DEPTH (thousands of ft)
0
4
8
12
16
20
24
28
32
36
40
STEEL
35
STEEL
50
ALUMINUM
25
STEEL
85
STEEL
110
STEEL
ALUMINUM
STEEL
150
50
FIBER GLASS & FLAKE GLASS
200
SPHERE GLASS
60
TITANIUM
15
ALUMINUM
150
STEEL
85
FIBER GLASS
150
300
ALUMINA CERAMIC
300
PYROCERAM
300
100
90
80
70
60
50
40
30
20
10
0
DISPLACED WATER (lb)-VESSEL WEIGHT (lb)
DISPLACED WATER (lb)
x 100

FIG 12